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Compost and Manure Effects on Sugarbeet Nitrogen Uptake, Nitrogen Recovery, and Nitrogen Use Efficiency

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ABSTRACT

To maximize recoverable sucrose from sugarbeet (*Beta vulgaris* L.), producers must effectively manage added N, be it from urea or organic sources such as manure or composted manure. Our study's objective was to determine the effects of a one-time application of stockpiled and composted dairy cattle (*Bos taurus*) manure on sugarbeet N uptake, nitrogen recovery (NR) and nitrogen use efficiency (NUE). First-year Site A treatments included a control (no N), urea (202 kg N ha^{-1}), compost (218 and 435 kg estimated available N ha^{-1}), and manure (140 and 280 kg available N ha^{-1}). Site B treatments were a control, urea (82 kg N ha^{-1}), compost (81 and 183 kg available N ha^{-1}), and manure (173 and 340 kg available N ha^{-1}). Compost and manure were incorporated into two silt loams, a Greenleaf (fine-silty, mixed, superactive, mesic Xeric Calciargid) near Parma, ID, in fall 2002 and 2003 and a Portneuf (coarse-silty, mixed, superactive, mesic Durinodic Xeric Haplocalcid) near Kimberly, ID, in fall 2002 with sugarbeet planted the following spring. At each site, N uptake of sugarbeet tops, but not roots, was similar whether fertilized with urea or organic N, regardless of rate. Incorporating equal organic amendment rates to 0.05 rather than 0.10 m increased whole-plant N uptake 1.13-fold, to 163.3 kg N ha^{-1}. In general, NR varied among fertilizer sources such that urea >> manure > compost. Where similar available N rates were supplied, NUE ranged from 44.1 to 83.5 kg sucrose kg^{-1} available N, not differing among inorganic and organic N sources within site-years.

Effective season-long N management is essential to profitably produce sugarbeet (Campbell, 2002). Early in the growing season, mineral N must be present in the upper soil profile to be taken up by the still developing root system of the sugarbeet (Martin, 2001; Jaggard et al., 2009). As the growing season progresses, N uptake from the entire profile must be well synchronized with the mineralization of N from organic sources. With poor synchronization, N added as inorganic fertilizer or mineralized from organic fertilizers can be taken up too late in the season to positively impact yield or, as NO_3–N, can be leached below the fibrous root system of the sugarbeet (Allison et al., 1996). In semiarid regions, NO_3–N leaching is less of a concern under sprinkler irrigation where water is typically well managed (Carter, 1984) than under furrow irrigation where water cannot be as well managed (Lehrsch et al., 2014). With furrow irrigation, NO_3–N leached to greater depths early in the season is available there for late-season sugarbeet uptake (Winter, 1986), which reduces sucrose yield (Carter and Traveller, 1981). Nitrogen in dairy cattle manure or composted manure, with significant portions in less mobile organic forms, might minimize this NO_3–N accumulation in lower portions of the sugarbeet root zone.

Many crop producers are aware that applying compost or manure to their soils can (i) increase soil organic carbon (SOC) and improve soil physical properties (Haynes and Naidu, 1998; Loveland and Webb, 2003), and (ii) increase nutrient availability (Robbins et al., 1997; Eghball et al., 2004). Despite these benefits, sugarbeet producers hesitate to apply compost and manure to their fields because it is difficult to predict the amount and timing of the N mineralized from the amendments. Nitrogen availability from manure and composted manure must be estimable, ideally from research utilizing in situ measurements (Lentz et al., 2011), to ensure sugarbeet of the highest quality (James, 1971). Nitrogen is mineralized at different rates from compost and manure, being generally greater from manure than compost (Eghball, 2000; Diacono and Montemurro, 2010). Nitrogen mineralization rates can also vary spatially depending on organic N characteristics, particularly where organic N sources are applied at low rather than high rates because low rates provide less of a buffer where N availability may be marginal (Lentz and Lehrsch, 2012b).

Dairy manure is readily available in many areas of the Intermountain West, in both the United States and southern

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Abbreviations: CNS, carbon-nitrogen-sulfur; NR, nitrogen recovery; NUE, nitrogen use efficiency; SOC, soil organic carbon

Canada. In Idaho alone in 2014, the approximate 565,000 dairy cattle produced more than 13.2 million Mg of manure (Nennich et al., 2005; NASS, 2014). On some dairy farms, producers compost manure (Richard, 2005) to reduce its mass, volume, weed seed viability, and odor to ease handling, improve storage and transport, and increase marketability (Draycott and Christenson, 2003; Larney et al., 2006). Relative to raw manure, on a per unit dry weight basis composted manure generally contains (i) more stable C compounds, (ii) less organic N, (iii) less NH_4–N, and, if little NO_3–N was lost via runoff or leaching during composting (iv) more NO_3–N (Eghball et al., 1997; Lehrsch and Kincaid, 2007). Without careful handling and timely incorporation, however, much of the NH_4–N in manure can be lost as NH_3 (Richard, 2005; Larney et al., 2006).

Few have studied the effects of compost or manure on the N uptake, recovery, and use efficiency of sugarbeet, though some have studied other crops such as small grain. Nitrogen uptake by barley (*Hordeum vulgare* L.) silage was similar between fresh and composted beef cattle manure after nine annual applications (Miller et al., 2009). Spring barley, including both grain and straw, recovered about 15% of the labeled N in manure and 40% of that in NH_4NO_3 in the first year after a fall application (Jensen et al., 1999). As a 5-yr average, a nutrient balance of 46 kg N (ha yr)$^{-1}$ (calculated as input less offtake) was measured where sugarbeet was grown with half of its N requirement supplied by manure and half by inorganic N fertilizer (Vos and van der Putten, 2000). Sugarbeet tops and roots recovered about 55% of labeled N in fall-applied urea, while leaving 43% in 1.8-m-deep profiles of a silty clay soil; organic N sources were not studied (Moraghan, 2004). In southern Idaho, only two studies of irrigated sugarbeet reported the recovery, uptake, or use efficiency of N. In those studies, however, researchers applied only conventional inorganic N fertilizer, either NH_4NO_3 (Carter, 1984), or urea (Tarkalson et al., 2012). Hence, research is particularly needed on N release from organic materials and, by extension, N uptake by treated crops (Cabrera et al., 2005). Thus, this field study's objective was to determine the effects of a one-time application of compost and manure on sugarbeet N uptake, N recovery and N use efficiency from silt loam soils in southwestern and south-central Idaho.

MATERIALS AND METHODS

Site A

Soils and Amendments. Site A was at the University of Idaho Parma Research and Extension Center in Parma, ID. The experiment was conducted from 2002 to 2004 on two fields, Field D-2 in 2002/2003 and Field E-5 in 2003/2004. We studied one-time amendment applications rather than ones repeated yearly because (i) one-time applications of relatively high amendment rates would greatly impact a producer's N management and could potentially decrease both the yield and quality of first-year sugarbeet (Lehrsch et al., 2015), (ii) one-time, high-rate applications would reduce a farmer's costs by potentially eliminating application costs for at least one succeeding crop, and (iii) we wished to study one-time, amendment application effects on a succeeding, second-year crop of wheat (*Triticum aestivum* L.) (findings to be presented in a later paper). A different field was used the second year to avoid carry-over impacts from previous applications of manure and compost. The soil at each field was a Greenleaf silt loam (Soil Survey Staff, 2010) (Table 1). Initial soil test N samples that were collected before any treatments were applied revealed that there was less inorganic N (NO_3–N + NH_4–N) but more organic C at Field D-2 than E-5 (Table 1). Before the current study, no organic N sources had been applied to either field for at least 10 yr.

Table 1. Soil properties of the two Greenleaf silt loams at Site A and the Portneuf silt loam at Site B (after Lehrsch et al., 2015).

Soil properties (0- to 0.3-m depth, or as noted)	Site A Field D-2 2002/2003	Site A Field E-5 2003/2004	Site B 2002/2003
Particle size distribution, g kg^{-1}			
Sand, 0.05–2 mm	330	300	140
Silt, 0.002–0.05 mm	600	550	660
Clay, <0.002 mm	70	150	200
Organic C, g kg^{-1}	6.4	5.5	8.4
pH, aqueous saturated paste	7.8	7.6	7.1
Electrical conductivity, dS m^{-1}	0.56	0.54	0.8
$CaCO_3$ equivalent, g kg^{-1}	67	42	75
Inorganic N†			
0 to 0.3 m, mg kg^{-1}	8.1	15.2	10.2
0.3 to 0.6 m, mg kg^{-1}	7.0	8.8	22.7
0 to 0.6 m, kg ha^{-1}	60	96	130

† Residual inorganic N (NO_3–N + NH_4–N) in fall before amendment application. Site B data is that present in the control at sugarbeet planting after a spring pre-irrigation and subsequent pre-plant rainfall (Lentz et al., 2011).

Solid manure, including straw as bedding, from dairy cattle was obtained from nearby sources each fall. The manure, never handled as a slurry, had been scraped from open pens and stockpiled through the summer in temporary, unconfined piles. Composted dairy manure was obtained from a different source, a south-central Idaho supplier who processed scraped, solid manure from many sources via windrow composting with mechanical turning. To determine the manure and compost application rates each year, we assumed that the portion of their total N contents that would be mineralized in the 12 mo following application would be 200 g N (kg total N)$^{-1}$ from compost and 400 g N (kg total N)$^{-1}$ from manure (Eghball and Power, 1999; Richard, 2005). The resulting estimates of first-year mineralized N were termed estimated available N. Each fall, we collected samples of each amendment just before application (described later). In fall 2002, dried samples of each amendment were ground to pass a 1-mm screen and their total C and N concentrations were determined by the dry combustion (Tabatabai and Bremner, 1991) of an approximate 400-mg sample in a vario MAX carbon-nitrogen-sulfur (CNS) analyzer (Elementar, Hanau, Germany). In fall 2003, the total N in each amendment was determined via the micro-Kjeldahl method with NH_4–N measured colorimetrically (Watson et al., 2003). Due to a change in research personnel in fall 2003, samples were discarded before total C had been measured. Compost and manure properties are given in Table 2.

Experimental Design and Treatments. The experiment, described in detail by Lehrsch et al. (2015), was designed as a randomized complete block with eight treatments and four replications (Table 3). First-year treatments consisted of a non-N-fertilized control, conventional N fertilizer (urea) applied at the University of Idaho recommended N rate of 202 kg N ha^{-1}

Table 2. Properties of the compost and manure applied to each site in fall of the year shown. Other than dry matter content, all measurements are on a dry-weight basis.

	Compost			Manure		
	Site A		Site B	Site A		Site B
Property	2002	2003	2002	2002	2003	2002
Total C, g kg^{-1}	282	nd†	163	162	nd	302
Total N, g kg^{-1}	20.5	15.7	14.2	16.0	22.1	18.6
C/N ratio	13.8	nd	11.5	10.1	nd	16.2
Dry matter content, kg kg^{-1}	0.65	0.65	0.74	0.65	0.40	0.60

† nd = not determined.

(Gallian et al., 1984), two rates of stockpiled, solid manure (21.9 and 43.8 Mg ha^{-1}, dry wt.) from dairy cattle, and two rates (53.1 and 106.1 Mg ha^{-1}, dry wt.) of composted dairy cattle manure (hereafter referred to simply as compost). The remaining two treatments were duplicates of the low rate of each amendment that were incorporated to 0.05 rather than 0.1 m (Table 3). The low and high rates of each amendment were chosen to apply estimated available N at rates equal to one and two times the recommended inorganic N rate of 202 kg N ha^{-1}, respectively. The recommended N rate was chosen based on a sugarbeet root yield goal of 67.2 Mg ha^{-1}, after accounting for the 0.6-m-deep profile's inorganic N that averaged 7.6 mg kg^{-1} (Table 1) present in the fall of 2002. No additional N fertilizer was added to the manure- or compost-treated plots. Compost at the rates we studied, though needed for balance among our treatments, would not be economical as a crop's sole N source. In southern Idaho, typical bulk amendment application rates (dry wt. basis) range up to 28 Mg ha^{-1} for compost and 55 Mg ha^{-1} for manure when applied annually. Typical application rates are less for compost than manure not because of differences in available N but because compost is (i) more expensive due to processing, (ii) less readily available, and (iii) higher in soluble salts.

Our attempts to apply compost and manure at rates which, in the first year after application, provided (i) a similar, and (ii) twice the amount of available N as that supplied by the urea-fertilized treatment were not successful (Table 3), principally due to laboratory-to-laboratory discrepancies in manure analysis. In fall 2002, one of two subsamples of compost and of manure were analyzed by a local feed testing laboratory to obtain quick but preliminary estimates of their total N, which were, in turn, used with assumed mineralization rates to calculate the amendments' bulk application rates (Table 3). We then applied the organic amendments at those rates in fall 2002. The second subsample of each was later analyzed using a CNS analyzer to measure its total N and C contents (Table 2). The CNS measurement of total N was used to calculate the estimated available N given in Table 3. The manure's preliminary estimate differed, however, from its subsequent measurement resulting in the first-year estimated available N rates from the 2003 manure treatments being about 31% less than our two targeted rates. Consequently, in 2003 the three compost treatments at Site A supplied about 1.55-fold more estimated available N than their corresponding manure treatments, on average (Table 3). As planned, however, the 2003 compost treatments did supply available N at rates equal to and twice that of the urea-fertilized treatment, in general (Table 3).

Field Operations. On 1 Oct. 2002, residue from a previous wheat crop was incorporated with a disk, then rototiller. The organic amendments were applied by hand to the 6.7 by 15.2 m plots on 6 to 8 Nov. 2002. Once applied, the compost was incorporated within about 7 h and the manure within

Table 3. Treatment descriptions and application rates of moisture-free bulk amendments and total N for sugarbeet grown in the year shown, along with an estimate of each treatment's total N that became available via mineralization in the year ending at sugarbeet harvest (after Lehrsch et al., 2015).

Treatment code†	Amendment	Bulk application rate‡ 2003	Bulk application rate‡ 2004	Depth of incorporation	Total N application rate 2003	Total N application rate 2004	Estimated available N§ 2003	Estimated available N§ 2004
		Mg ha^{-1}	Mg ha^{-1}	m	kg N ha^{-1}			
Site A								
Ctrl-A	None	0	0	0	0	0	0	0
Fert-A	Urea	0.44	0.44	0.05¶	202	202	202	202
Com1s-A	Compost	53.1	64.2	0.05	1089	1008	218	202
Com1-A	Compost	53.1	64.2	0.10	1089	1008	218	202
Com2-A	Compost	106.1	128.4	0.10	2175	2016	435	403
Man1s-A	Manure	21.9	22.8	0.05	350	504	140	202
Man1-A	Manure	21.9	22.8	0.10	350	504	140	202
Man2-A	Manure	43.8	45.6	0.10	701	1008	280	403
Site B								
Ctrl-B	None	0	–#	0	0	–	0	–
Fert-B	Urea	0.18	–	0.07	82	–	82	–
Com1-B	Compost	28.4	–	0.10	403	–	81	–
Com2-B	Compost	64.3	–	0.10	913	–	183	–
Man1-B	Manure	23.3	–	0.10	433	–	173	–
Man2-B	Manure	45.7	–	0.10	850	–	340	–

† Ctrl, Fert, Com, Man = Control, Fertilizer (urea), Compost, or Manure, respectively; 1s, 1, 2 = Rate 1 shallowly incorporated to 0.05 m, Rate 1 incorporated to 0.10 m, or Rate 2 incorporated to 0.10 m, respectively;-A,-B = Site A or Site B, respectively.

‡ Organic amendments were applied in the fall preceding the year shown.

§ Calculated assuming a first-year mineralization of 200 g N (kg total N)$^{-1}$ from compost and 400 g N (kg total N)$^{-1}$ from manure (Eghball and Power, 1999; Richard, 2005).

¶ On 5 May 2003, 56 kg N ha^{-1} was broadcast, then lightly incorporated, with 67 kg N ha^{-1} subsequently sidedressed to the 0.05-m depth on 4 June, and the remaining 79 kg N ha^{-1} sidedressed 13 d later. In spring 2004, 101 kg N ha^{-1} was sidedressed to the 0.05-m depth on 14 May, with the remaining 101 kg N ha^{-1} sidedressed on 2 June.

– = none.

about 31 h using a rototiller. Thereafter, tool-bar mounted shovels were used to form beds every 0.56 m across the plots on 8 Nov. 2002. Based on soil tests from the previous fall, on 1 Apr. 2003 the entire field was uniformly top-dressed with P, K, and B (Lehrsch et al., 2015). The fertilizer was lightly incorporated as the furrows were reestablished with shovels on a tool-bar before planting. Three days later, bed tops were removed and sugarbeet was planted in a row centered atop each bed. The conventional N treatment was applied as a split application after stand establishment to enhance N use efficiency and N uptake (Carter and Traveller, 1981; Hergert, 2010). To the conventionally fertilized plots only, 56 kg N ha^{-1} (as urea) was broadcast on 5 May 2003, followed by a sidedress application of 67 kg N ha^{-1} (as urea) on 4 June and a second of 78 kg N ha^{-1} (as urea) on 17 June. The site was furrow irrigated about 14 times each year with the crop managed using locally standard production practices (Panella et al., 2014). Just after being mechanically topped, the sugarbeet was harvested on 27 Oct. 2003.

The trial was repeated on a different field (E-5) for the 2003/2004 season using, in general, the same or similar field operations performed at about the same times as for the earlier trial, with the following exceptions. Initial soil test N samples were collected on 24 November but had not yet been analyzed when the amendments had to be applied. Consequently, we estimated the inorganic N content of the second-year profile to be similar to that of the first-year and applied, then incorporated the organic N sources accordingly on 28 Nov. 2003, again within about 31 h of their application. In actuality, our estimate of residual inorganic N content was 60% too low (Table 1) and, in consequence, the inorganic N fertilizer applied in spring (that by design had to match the already applied organic sources) was greater than that recommended (Gallian et al., 1984). With no additional non-N fertilizer applied, sugarbeet was planted the following spring. Of the 202 kg N ha^{-1} (as urea) applied in 2004 to the conventional (Fert-A) treatment, half was sidedressed on 14 May and half on 2 June. Rainfall and excessively wet soil delayed the fall 2004 sugarbeet harvest until 22 November.

Sample Collection and Analyses. Eight soil samples (0–0.3 and 0.3–0.6 m) were collected from the field on 16 Oct. 2002, then composited by depth to determine the baseline contents of inorganic N (NO_3–N + NH_4–N), P, K, and selected micronutrients at the site. Three days before sugarbeet harvest, total biomass of tops (i.e., petioles and leaves) and roots were collected from 1.52 m of one row in each plot on 24 Oct. 2003. Each tissue sample was weighed fresh. Thereafter, about 1.8-kg subsamples of roots, having been shredded after weighing, and about 0.7-kg subsamples of tops were collected, weighed, dried at 60°C for approximately 3 or 4 d, then re-weighed to determine their dry matter content. Whole-plant biomass was calculated by summing the masses of the dry tops and dry roots. Each dry subsample was ground to pass a 1-mm screen and its N concentration determined via dry combustion as was that of the manure and compost in the fall of 2002. The N uptake by the tops, roots, and whole plants were determined by multiplying the dry mass of each component by its N content. All tissue samples subsequently collected in 2004 were analyzed as in 2003. Sugarbeet yield was reported earlier by Lehrsch et al. (2015).

The sugarbeet's apparent nitrogen recovery (NR, as percent of total N applied) for each treatment except the control was calculated (Wen et al., 2003) as:

$$\mathrm{NR} = \frac{\left(\mathrm{N\ Uptake}_{\mathrm{Trt}} - \mathrm{N\ Uptake}_{\mathrm{Ctrl}}\right)}{\mathrm{N\ Applied}_{\mathrm{Tot,\,Trt}}}(100) \qquad [1]$$

where N Uptake$_{\mathrm{Trt}}$ was the treatment's whole-plant N uptake (kg N ha^{-1}), N Uptake$_{\mathrm{Ctrl}}$ was the control's whole-plant N uptake (kg N ha^{-1}), and N Applied$_{\mathrm{Tot,Trt}}$ was the treatment's total N applied (kg N ha^{-1}, Table 3). In addition, the sugarbeet's agronomic N use efficiency [NUE, kg sucrose (kg available N)$^{-1}$] for each treatment except the control was calculated (Moll et al., 1982) as:

$$\mathrm{NUE} = \frac{\mathrm{Sucrose\ Yield}_{\mathrm{Trt}}}{\mathrm{N\ Applied}_{\mathrm{Avail.,\,Trt}}} \qquad [2]$$

where Sucrose Yield$_{\mathrm{Trt}}$ was the treatment's sucrose yield (kg sucrose ha^{-1}, reported earlier by Lehrsch et al., 2015) and N Applied$_{\mathrm{Avail.,Trt}}$ was the treatment's estimated available N applied (kg available N ha^{-1}). Each treatment's estimated available N was the estimate of N mineralized in the first 12 mo after the amendment was applied (Table 3). The NUE values calculated using Eq. [2] were based on the available N supplied solely by the amendment, not the soil and amendment (Moll et al., 1982).

Site B

Soils and Amendments. Site B, in southern Idaho near the USDA-ARS Northwest Irrigation and Soils Research Laboratory, Kimberly, ID, was on a Portneuf silt loam (Table 1). The residual inorganic N in the soil, first measured the preceding fall, was decreased by a needed spring pre-irrigation and subsequent, untimely pre-plant rainfall. Thus, the Portneuf's inorganic N measured in the control at sugarbeet planting has been given in Table 1. The Portneuf soil at Site B contained 1.67-fold more residual inorganic N than the two Greenleaf soils at Site A, on average. The field at Site B had received no organic N sources since 1994.

The experimental methods used at Site B have been described in detail by Lentz et al. (2011). In brief, the amendment rates studied at Site B were also established assuming that the N mineralized in the first year would be 200 g N (kg total N)$^{-1}$ from compost and 400 g N (kg total N)$^{-1}$ from manure. At Site B, we studied six of the eight treatments described for Site A (Table 3). The amendment properties are shown in Table 2 and application rates of the bulk amendments and estimated available N added are shown in Table 3. Samples of solid manure (never a slurry) and compost were collected, then weighed on 24 Oct. 2002, the day both were incorporated by disking. Subsamples of each were freeze-dried and subsequently analyzed to determine their total C and N contents (Nelson and Sommers, 1996) by combusting a 25-mg sample in a Thermo-Finnigan FlashEA1112 CNS analyzer (CE Elantech Inc., Lakewood, NJ).

Experimental Design and Treatments. The experiment at Site B was part of a larger study that examined organic amendment effects on both eroded and non-eroded portions of

Portneuf silt loam (Lentz et al., 2011). The current study presents findings that were not reported by Lentz et al. (2011) from six treatments applied only to non-eroded soil at Site B. Here, as at Site A, the design was a randomized complete block with four replications of six treatments: an unamended control (that received no N fertilizer), a fertilized treatment that received urea at the recommended rate, two compost treatments, and two manure treatments (Table 3). The compost treatments supplied the sugarbeet with estimated available N equal to about one times (1x) and two times (2x) the N supplied by the urea fertilizer treatment. The Man1-B application rate of 23.3 Mg ha^{-1} (Table 3) was chosen, in part, because it was common in the region. It was doubled to provide the Man2-B rate. The Man1-B and Man2-B rates were also chosen to supply, in general, the same total N, though inadvertently twice the available N, as did the Com1-B and Com2-B rates, respectively (Lentz et al., 2011). A sugarbeet root yield goal of 76 Mg ha^{-1} resulted in an urea-N application rate of 82 kg N ha^{-1} (Table 3), after accounting for the inorganic N content in the 0.60-m profile.

Field Operations. The entire site was planted with Stephens winter wheat in mid-August 2002. Seven weeks later, without being harvested the wheat as a green manure was killed with herbicide, then incorporated by disking and roller harrowing. After solid manure was applied with a commercial spreader truck on 10 October, compost was applied using a calibrated rotary spreader mounted on a 9-Mg truck on 22 Oct. 2002. Both amendments were incorporated to a depth of 0.1 m by disking about 48 h later. On 29 Oct. 2002, urea was applied to the appropriate plots by hand, the entire field was sprayed with herbicide, then all materials were immediately incorporated with a roller-harrow. Thereafter, the field was tilled to form beds every 0.56 m across the 9-m wide by 21-m long plots in preparation for sugarbeet planting the following spring. After pre-irrigating in late April, sugarbeet was planted on 21 May 2003, then irrigated with sprinklers about 20 times throughout the season. Unlike Site A, the trial at Site B was not repeated for a second year.

Sample Collection and Analyses. Total biomass of sugarbeet tops and roots were measured from a 1.5-m-long portion of one row on 13 Oct. 2003, 1 d before harvest. Biomass samples at Site B were processed and analyzed, in general, as were biomass samples at Site A, but with the following exceptions. Subsamples of the biomass dried at 65°C were ground to pass an 865-µm screen and their total N concentrations determined as were those of the amendments at Site B. The apparent N recovery and agronomic N use efficiency of the sugarbeet at Site B were determined in the same manner as at Site A.

Statistical Analysis

We analyzed the data by site using a mixed-model ANOVA using the PROC Mixed procedure in SAS (SAS Institute Inc., 2009) with a significance probability (P) of 0.05, unless otherwise noted. The statistical model for Site A had treatment and year as fixed effects and block(year) as the random effect while that for Site B had treatment as fixed and block as random. When needed, ANOVA grouping options accounted for heterogeneous variances among treatments for each response variable. For all significant fixed effects, we separated least-squares means using the Tukey–Kramer multiple comparison test with letter groupings assigned using software written by Saxton (1998). In addition, we constructed single-degree-of-freedom contrasts to test for differences among groups of related treatments, averaged across years for Site A. A preliminary analysis examined each response variable's error variance by treatment using the relationship between the variable's treatment means and corresponding treatment standard deviations (Lehrsch and Sojka, 2011). We used a common log or, at times, square root transformation to stabilize the error variance of a variable, as needed. In those cases, means were back-transformed into original units for presentation.

RESULTS AND DISCUSSION

Site A

Treatments affected the biomass and N uptake of every plant component (tops, roots, and whole plants) while year influenced N uptake by roots and whole plants (Table 4). Treatment effects on root N uptake varied depending on year. Because of the structure that we planned in our treatments (Table 3), single degree-of-freedom contrasts, that is, class comparisons, most

Table 4. Treatment, year, and contrast effects on sugarbeet response variables at Site A. Contrast effects are averaged across years and, where footnoted, across treatments.

	ANOVA $P > F$					
	Biomass			N uptake		
Source of variation	Tops	Roots	Whole plant	Tops	Roots	Whole plant
Treatment	***	***	***	***	***	***
Year	0.34	0.24	0.35	0.82	**	*
Treatment × Year	0.82	0.45	0.55	0.53	*	0.08
Contrast†						
Shallow vs. Deep	0.28	0.63	0.52	0.21	0.21	*
Fert vs. Com1&2	0.84	0.92	0.97	0.39	0.12	0.44
Fert vs. Man1&2	0.10	0.37	0.20	0.66	0.06	0.08
Com_All vs. Man_All	*	*	*	*	*	**
Com1_both vs. Com2-A	0.07	0.06	*	**	***	***
Man1_both vs. Man2-A	*	0.06	*	**	***	***

* Significant at $P = 0.05$.

** Significant at $P = 0.01$.

*** Significant at $P = 0.001$.

† Shallow = Com1s-A + Man1s-A; Deep = Com1-A + Man1-A; Fert = Fert-A; Com1&2 = Com1-A + Com2-A; Man1&2 = Man1-A + Man2-A; Com_All = Com1s-A + Com1-A + Com2-A; Man_All = Man1s-A + Man1-A + Man2-A; Com1_both = Com1s-A + Com1-A; Man1_both = Man1s-A + Man1-A.

easily summarize our findings (Table 4). Among the contrasts, (i) incorporation depth affected whole-plant N uptake averaged across amendments and (ii) organic N source affected the biomass and N uptake of each plant component (Table 4). The last two contrasts in Table 4 tested for differences between the amendment's high rate and its two low rates considered as a class (e. g., Com1_both = Com1s-A+Com1-A). Each amendment's two low rates, though incorporated to different depths, were considered as a class because our statistical analysis revealed that there were no differences in either biomass or N uptake between the two individual compost treatments or between the two individual manure treatments (discussed later). Those class comparisons, Com1_both vs. Com2-A and Man1_both vs. Man2-A, were often significant for biomass and always for N uptake by plant component (Table 4). Their significance revealed that organic amendment rate affected both biomass and N uptake for specific plant components, as discussed later.

Treatment Effects

Depth of Incorporation. Incorporation depth, 0.05 vs. 0.10 m, had no effect on N uptake, regardless of plant component, by either amendment where low (i. e., similar) rates were applied (Table 5). This finding suggests that N loss as ammonia via volatilization after incorporation, if it occurred, did not differ between incorporation depths for either amendment. One might speculate that volatilization of ammonia from manure might be greater with shallow rather than deep incorporation but we found no evidence to support such a view (Table 5). Thus, the shallow and deep treatments of the low rate of each amendment were often considered together as a class. When averaged across amendments and years, however, the shallow vs. deep contrast showed that incorporating organics to a shallower rather than deeper depth increased N uptake by whole plants (Table 5). While sugarbeet can root to depths of nearly 2 m in moist soil profiles without root-restrictive layers, about 35% of the plant's roots are in the profile's uppermost 0.3 m (Blumenthal, 2001; Yonts and Palm, 2001). Lower bulk density and likely greater water retention (not measured) where a similar rate of amendment was incorporated to 0.05 rather than 0.10 m may have spurred early-season sugarbeet growth and development. Faster growth with shallow incorporation would have enabled the young sugarbeet with small root systems to take up the amendments' supplied inorganic N, and P, K, and micronutrients, and recently mineralized N (i) to develop full canopies relatively early in the growing season to intercept incoming radiation (Blumenthal, 2001; Jaggard et al., 2009), and thereby (ii) to more quickly establish a deep root system to acquire inorganic N, both subsurface residual and that mineralized through the season (Lentz et al., 2011). Indeed, as Brown et al. (2006) reported, in the one instance when in-season uptake differed with incorporation depth, early-season N uptake was greater with shallow rather than deep

Table 5. Treatment, year, and contrast effects on sugarbeet response variables at Site A. Yearly means are averaged across treatments while both treatment and contrast means are averaged across years.

Source of variation	Biomass			N uptake		
	Tops	Roots	Whole plant	Tops	Roots	Whole plant
	Mg ha^{-1}			kg N ha^{-1}		
Treatment						
Ctrl-A	2.43 c†	11.7 c	14.2 c	40.1 d	62.4	103.1 d
Fert-A	3.73 ab	16.8 ab	20.5 ab	63.3 abc	120.1	187.0 a
Com1s-A	3.70 ab	17.2 ab	20.9 ab	64.6 abc	111.4	181.6 ab
Com1-A	3.33 abc	15.5 ab	18.8 abc	57.5 bcd	84.4	145.7 bc
Com2-A	4.02 a	18.3 a	22.4 a	78.8 a	132.0	211.5 a
Man1s-A	3.10 abc	14.2 bc	17.3 bc	54.3 bcd	88.8	145.0 bc
Man1-A	2.89 bc	15.2 abc	18.0 b	49.9 cd	86.9	142.3 cd
Man2-A	3.69 ab	16.7 ab	20.4 ab	71.6 ab	120.2	194.6 a
Year						
2003	3.58	15.0	18.6	61.1	84.6	148.2 b
2004	3.14	16.4	19.5	58.9	114.0	179.6 a
Contrast‡						
Shallow vs.	3.40	15.7	19.1	59.5	100.1	163.3 a
Deep	3.11	15.4	18.4	53.7	85.6	144.0 b
Fert vs.	3.73	16.8	20.5	63.3	120.1	187.0
Com1&2	3.67	16.9	20.6	68.2	108.2	178.6
Fert vs.	3.73	16.8	20.5	63.3	120.1	187.0
Man1&2	3.29	16.0	19.2	60.8	103.6	168.4
Com_All vs.	3.68 a	17.0 a	20.7 a	67.0 a	109.3 a	179.6 a
Man_All	3.22 b	15.4 b	18.6 b	58.6 b	98.6 b	160.6 b
Com1_both vs.	3.51	16.4	19.8 b	61.0 b	97.9 b	163.6 b
Com2-A	4.02	18.3	22.4 a	78.8 a	132.0 a	211.5 a
Man1_both vs.	2.99 b	14.7	17.6 b	52.1 b	87.8 b	143.6 b
Man2-A	3.69 a	16.7	20.4 a	71.6 a	120.2 a	194.6 a

† For a given response variable, treatment, year, or contrast means followed by a common letter were not significantly different at $P = 0.05$. No letters are shown if (i) the effect was not significant in the ANOVA, or (ii) an interaction was significant.

‡ Shallow = Com1s-A + Man1s-A; Deep = Com1-A + Man1-A; Fert = Fert-A; Com1&2 = Com1-A + Com2-A; Man1&2 = Man1-A + Man2-A; Com_All = Com1s-A + Com1-A + Com2-A; Man_All = Man1s-A + Man1-A + Man2-A; Com1_both = Com1s-A + Com1-A; Man1_both = Man1s-A + Man1-A.

incorporation. Transient changes in near-surface soil water contents and soil temperatures with furrow irrigation may also have affected N mineralization, immobilization, or both, differently with depth (Lentz and Lehrsch, 2012a). Any one or more of these postulated mechanisms may have accounted, at least in part, for the greater whole-plant N uptake for the shallow rather than deep-incorporated treatments (Table 5). Allison et al. (1996) reported that deep incorporation of organic amendments in sugarbeet production fields increased N losses, presumably by leaching.

Differences between Organic Amendments and the Control or Fertilizer. Sugarbeet biomass and N uptake were often greater for the fertilizer treatments, whether organic or inorganic, or shallowly or deeply incorporated, than the control, Ctrl-A (Table 5). The Com2-A treatment, which provided the most available N in 2003 and equal to the most in 2004 (Table 3), produced the greatest mean biomass and N uptake of all treatments, though often statistically similar to other treatments (Table 5). The Com2-A treatment, though having no effect on sucrose content, did impair sugarbeet quality by increasing the conductivity and nitrate of the brei (finely ground root tissue from the shredding of washed and crowned roots; Campbell, 2002), relative to the urea-fertilized treatment (Lehrsch et al., 2015). Brei nitrate for the Com2-A treatment was 2.2-fold greater (significant at $P < 0.05$) than that for Fert-A (Lehrsch et al., 2015). This more-than-double brei nitrate is logical since approximately twice as much available N was provided by the Com2-A than Fert-A treatment (Table 3). Brei nitrates increase as in-season soil NO_3–N concentrations increase (Winter, 1986). Whole-plant N uptake was greater where fertilized with urea (Fert-A) than with the deeper-incorporated low rate of either amendment (Com1-A or Man1-A). This finding of greater whole-plant N uptake further supports the advantage of shallower rather than deeper placement of organic amendments, as discussed above. The N uptake by tops, averaged across years (Table 5) was similar among conventional N fertilizer and all rates of both amendments. The N uptake by whole plants, however, was similar only between urea and (i) the high rate of each amendment, and (ii) the Com1s-A treatment (Table 5).

The biomass and N uptake of sugarbeet tops, roots, and whole plants did not differ between the conventional, inorganic N fertilizer treatment and either of the organic amendments as a class (see contrasts in Table 5 that compared Fert-A with either the Com1&2 class [being Com1-A + Com2-A] or the Man1&2 class). This finding shows that, where organic amendments had been incorporated to a depth of 0.10 m, sufficient organic N had been mineralized to meet the N requirement of the sugarbeet while sustaining root and sucrose yields (Lehrsch et al., 2015). This is a significant benefit that would accrue to producers who utilize compost, manure, or both, to satisfy the N needs of their sugarbeet.

Differences between Compost and Manure. Compared to a contrast class consisting of the three manure treatments (Man_All = Man1s-A + Man1-A + Man2-A), the three compost treatments as a class (Com_All) increased the biomass and N uptake of every plant part (Table 5). These increases in biomass and N uptake were due in large part to the approximately 1.55-fold more available N applied by the compost than manure class in 2003 (Table 3). The compost class' greater available N, however, did not decrease its sucrose concentration as often occurs (Campbell, 2002) and, as a consequence, resulted in nearly 1.10-fold more recoverable sucrose than with manure (Lehrsch et al., 2015).

Contrasts were also used to test for rate differences within amendments. Compared to the Com1s-A and Com1-A treatments as a class (e. g., Com1_both), the Com2-A treatment increased whole-plant biomass and all measures of N uptake (Table 5). These increases were almost surely due to the greater available N in the Com2-A treatment than in the Com1s-A and Com1-A treatments (Table 3). Increasing the compost application rate (dry-weight basis) from 53.1 to 106.1 Mg ha^{-1} in 2003 and from 64.2 to 128.4 Mg ha^{-1} in 2004 increased sugarbeet N uptake in all plant components by at least 1.3-fold (Table 5). Manure rate effects were similar, in general, to compost rate effects on sugarbeet responses. Compared to the Man1s-A and Man1-A treatments as a class (e. g., Man1_both), the Man2-A treatment also increased N uptake of whole plants by 1.35-fold (and other components by even more) (Table 5). In addition, the Man2-A treatment increased top biomass by 1.23-fold and whole-plant biomass by 1.16-fold, relative to the Man1_both class. Overall, doubling the N available from compost and from manure decisively altered sugarbeet responses.

Year Effects

Root N uptake varied by year, though dependent on treatment (Table 4). Though statistically indistinguishable, overall root N uptake was nearly 1.35-fold greater in 2004 than in 2003 (Table 5). The tendency for root N uptake to be greater in 2004 than 2003 may have been due to 1.6-fold more residual inorganic N in the 0.6-m profile (Table 1), more available N being applied by the manure treatments (Table 3), or both. Another factor that contributed to poor N uptake in 2003 was compacted soil (Lehrsch et al., 2015) that physically limited fibrous rooting and storage root penetration, development, and enlargement (Baver and Farnsworth, 1941; Smith, 2001) that, in turn, decreased the yields of roots and sucrose in 2003 relative to 2004 (Lehrsch et al., 2015). Moreover, inorganic N could have been lost in 2003 via denitrification (not measured) from anaerobic microsites in transient saturated areas in Field D-2's compacted zones, that likely had poorer structure, greater bulk density, and fewer large pores to maintain adequate aeration (Nieder et al., 1989; McNeill et al., 2005). Thus, in fall 2003 next year's field (E-5) was subsoiled to the 0.3-m depth following winter wheat harvest but before amendment application and fall bedding. Whole-plant N uptake was 1.21-fold greater in 2004 than 2003 (Table 5), due at least in part to subsoiling, one might assume.

Treatment × Year Interaction

Root N uptake varied from treatment to treatment but the responses depended on year (Table 4). The response of each treatment was similar, in general, between years with one exception, that of Com1s-A (Fig. 1). Relative to Com2-A, root N uptake for Com1s-A was smaller in 2003 but larger, and statistically similar, in 2004. The subsoiling of Field E-5 may have benefited the Com1s-A treatment the most, possibly by enabling its sugarbeets' fibrous root systems to acquire inorganic N below the 0.3-m subsoiling depth, as discussed by Lehrsch et al. (2015). It is not

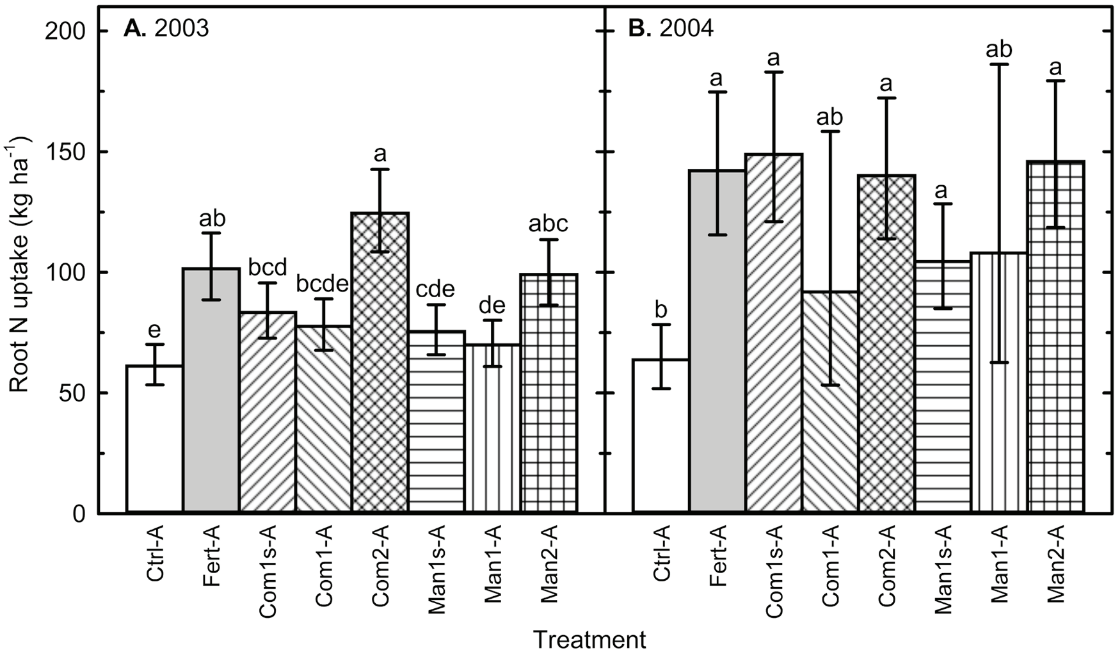

Fig. 1. Sugarbeet root N uptake by treatment each year at Site A. Within a year, means (n = 4, shown with 95% confidence limits) with a common letter were not significantly different at P = 0.05. Root N uptake differed between years only for the Com1s-A treatment.

apparent why subsoiling did not benefit the root N uptake of the Man1s-A treatment to the same degree as that of Com1s-A (Fig. 1). These differing responses between shallowly incorporated compost and manure (i) reveal why incorporation depth effects on N uptake averaged across amendment treatments differed among plant components (Table 4), and (ii) suggest that factors other than incorporation depth affect the N uptake, by roots at least, of each amendment. The numerous differences in root N uptake among treatments in 2003 relative to 2004 (Fig. 1) is because variability among replications within treatments was much less in 2003 than 2004 (Fig. 1). In 2003 where rooting depth was limited by compaction, sugarbeet roots in each plot likely fully explored the available root zone, efficiently scavenging the inorganic N present (Tarkalson et al., 2012). In 2004, in contrast, where rooting was unrestricted after subsoiling, normally expected plot-to-plot variability in root system development and rooting depth (not measured) likely occurred, thereby increasing variability in N uptake among treatment replicates (Fig. 1). Alternatively, soil N may have varied less in Field D-2 in 2003 than in Field E-5 in 2004, despite the fields having similar cropping and tillage histories.

Nitrogen Recovery and Use Efficiency

Sugarbeet nitrogen recovery (NR) in the first year differed among treatments (P < 0.001) and between years (P = 0.021) with no significant interaction present (P = 0.09). The Fert-A treatment recovered 41% of its total applied N, much more than any of the organic treatments (Table 6), likely because it supplied inorganic N that required no microbially mediated mineralization before uptake. In comparison, sugarbeet recovered an average of only 5.4% of the total N in compost and 8.2% of the total N in manure (Table 6), because much of the total N those sources provided remained in the organic form, not yet mineralized. The current study's first-year recoveries of N from both fall-applied inorganic and organic sources (Table 6) compare favorably with the 40% recovery from NH_4NO_3 and 15% recovery from manure by spring barley reported by Jensen et al. (1999). Moreover, the N recoveries shown in Table 6 generally lie within the ranges for manure, compost, and inorganic N fertilizer reported by Miller et al. (2009). Recovery of total N was 7.5% in 2003 but 1.73-fold greater, 13.0%, in 2004, when averaged across treatments (data not shown in tabular form). Regardless of the amendment applied, recovery was less in 2003 than 2004 because, among other factors, sugarbeet rooting in 2003 was restricted by compaction (Lehrsch et al., 2015). The 1.73-fold greater recovery in 2004 than 2003 suggests that, of the added organic N that was mineralized then nitrified, a substantial portion as NO_3–N may have been leached below 0.24 m, the depth of the compacted zone in Field D-2 in 2003. We speculate that some of that leached N was recovered by sugarbeet roots growing below 0.24 m in the subsoiled Field E-5 in 2004.

The agronomic nitrogen use efficiencies (NUEs) for sugarbeet each year are shown in Fig. 2. As expected (Carter, 1984; Raun and Johnson, 1999), the NUE each year decreased with increasing applications of available N, regardless of the amendment used (Fig. 2A and 2B). In 2003, 36% less available N was applied by the manure than compost treatments that year (Table 3) and, as

Table 6. Sugarbeet nitrogen recovery (NR) for Site A. Data have been averaged across years (the interaction was not significant at P = 0.09).

Treatment	Nitrogen recovery†
	%
Fert-A	41.0 a‡
Com1s-A	7.1 bc
Com1-A	3.9 c
Com2-A	5.1 bc
Man1s-A	8.4 bc
Man1-A	5.8 bc
Man2-A	10.5 b

† The recovered portion of the total nitrogen applied by the treatment.
‡ Means followed by a common letter were not significantly different at P = 0.05.

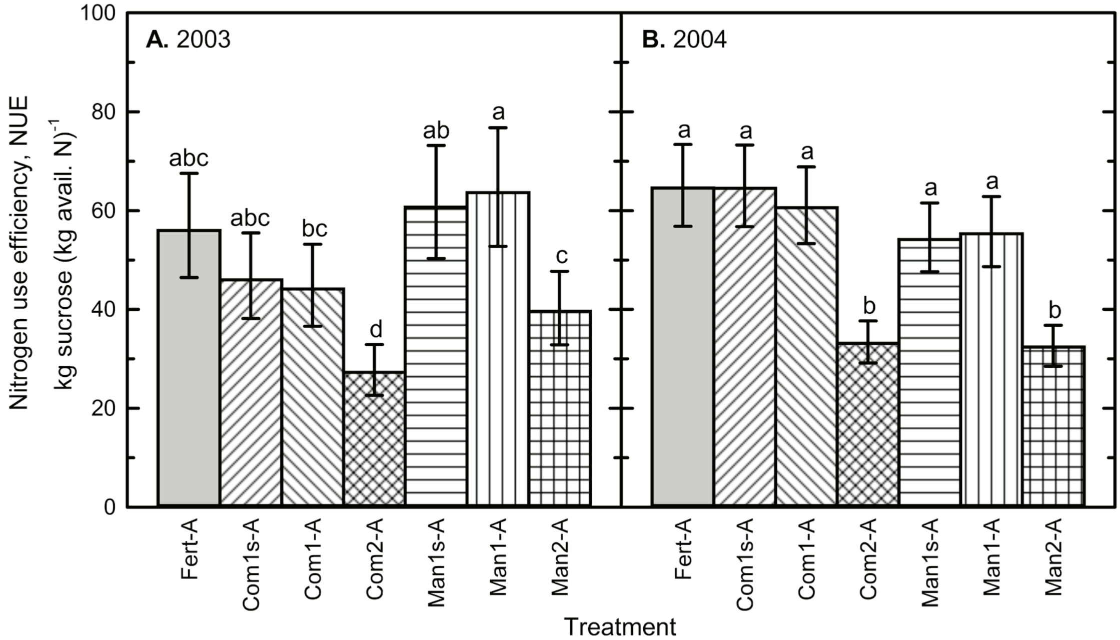

Fig. 2. Agronomic nitrogen use efficiency (NUE) for sugarbeet by treatment each year at Site A. Within a year, means (n = 4, shown with 95% confidence limits) with a common letter were not significantly different at P = 0.05. The NUE did not differ between years for any treatment.

a consequence, the NUE was greater for Man1-A than Com1-A and for Man2-A than Com2-A (Fig. 2A). Also in 2003, every treatment except Com2-A exhibited an NUE similar to that of Fert-A (Fig. 2A). In 2004, sugarbeet in the Com2-A and Man2-A treatments used N less efficiently than the sugarbeet in any other treatment (Fig. 2B) because sugarbeet in those two treatments were supplied with 403 kg available N ha^{-1}, nearly twice the 202 kg available N ha^{-1} supplied by the others, save the control (Table 3). The NUEs were similar among the Fert-A, Com1s-A, Com1-A, Man1s-A, and Man1-A treatments in 2003 (Fig. 2A) and in 2004 (Fig. 2B). This finding reveals that N mineralized from organic sources in the first year was used as efficiently as N from an inorganic source, as long as all sources provided approximately similar amounts of available N (Table 3). The NUE values reported here are similar to those measured by Tarkalson et al. (2012) for conventionally fertilized sugarbeet in south-central Idaho, also grown in a silt loam.

Site B

Sugarbeet biomass and N uptake at Site B (Table 7) were less affected by amendment treatments than at Site A (Table 4). The few responses at Site B may have been due to sufficient available soil N already present at study initiation. When the studies were begun, there was 1.67-fold more residual inorganic N in the soil profile at Site B than A, on average (Table 1), thereby making the sugarbeet less dependent on and less responsive to added N, whatever its source, at Site B than A. The sugarbeet root yield in the non-N-fertilized control was 56.3 Mg ha^{-1} at Site B, nearly 2 Mg ha^{-1} greater than the 2-yr average at Site A (Lehrsch et al., 2015). Moreover, plants may have responded less to applied N where daylengths were shorter, as at Site B, than longer, as at Site A (A. Moore, personal communication, 2014). The N uptake was similar for tops, though not roots, and for whole plants whether fertilized with conventional inorganic N or with compost or manure, regardless of the rate applied (Table 8).

Contrasts revealed, however, some differences between classes in sugarbeet biomass and N uptake (Table 8). Top and whole-plant biomass were less when fertilized with the compost of the Com1-B and Com2-B treatments (as a class) than with the urea of the Fert-B treatment. These differences, and more, carried on to the N uptake findings (Table 8). Relative to urea fertilization, beet N uptake where fertilized with the two compost treatments as a class (i. e., Com1&2) was significantly less and with the two manure treatments as a class

Table 7. Treatment and contrast effects on response variables for sugarbeet at Site B.

	ANOVA $P > F$					
	Biomass			N uptake		
Source of variation	Tops	Roots	Whole plant	Tops	Roots	Whole plant
Treatment	0.10	0.35	0.12	0.14	**	*
Contrast†						
Fert vs. Com1&2	**	0.14	*	*	**	**
Fert vs. Man1&2	0.24	0.93	0.62	0.13	1.00	0.25
Com1&2 vs. Man1&2	0.14	0.06	*	0.35	***	*

* Significant at P = 0.05.

** Significant at P = 0.01.

*** Significant at P = 0.001.

† Fert = Fert-B; Com1&2 = Com1-B + Com2-B; Man1&2 = Man1-B + Man2-B.

Table 8. Treatment and contrast effects on response variables for sugarbeet at Site B.

Source of variation	Biomass			N uptake		
	Tops	Roots	Whole plant	Tops	Roots	Whole plant
	Mg ha^{-1}			kg N ha^{-1}		
Treatment						
Ctrl-B	3.41	13.10	16.51	97.5	120.6 bc†	218.0 b
Fert-B	5.49	14.51	20.00	156.5	151.2 ab	307.7 a
Com1-B	3.97	12.97	16.95	118.7	113.0 c	231.7 ab
Com2-B	3.94	13.04	16.97	110.5	120.0 bc	230.5 ab
Man1-B	4.70	14.27	18.97	127.7	142.1 abc	269.9 ab
Man2-B	4.78	14.92	19.70	128.9	160.2 a	289.1 ab
Contrast‡						
Fert vs.	5.49 a	14.51	20.00 a	156.5 a	151.2 a	307.7 a
Com1&2	3.95 b	13.00	16.96 b	114.6 b	116.5 b	231.1 b
Fert vs.	5.49	14.51	20.00	156.5	151.2	307.7
Man1&2	4.74	14.60	19.34	128.3	151.2	279.5
Com1&2 vs.	3.95	13.00	16.96 b	114.6	116.5 b	231.1 b
Man1&2	4.74	14.60	19.34 a	128.3	151.2 a	279.5 a

† For a given response variable, treatment or contrast means followed by a common letter were not significantly different at $P = 0.05$. No letters are shown if (i) the effect was not significant in the ANOVA, or (ii) an interaction was significant.

‡ Fert = Fert-B; Com1&2 = Com1-B + Com2-B; Man1&2 = Man1-B + Man2-B.

was numerically less, in most cases. Though N uptake differed significantly among these treatments at Site B, sugarbeet quality and sucrose yield did not (Lehrsch et al., 2015). This finding was unexpected since the organic amendments relative to the Fert-B treatment applied one-fold to four-fold more available N (Table 3) and are thought to release greater amounts of available N in late summer, decreasing crop quality (Carter and Traveller, 1981; Blumenthal, 2001; Moore et al., 2009). Nitrogen immobilization in the organically amended treatments was likely responsible (Wen et al., 2003). Studying the same soil, Lentz et al. (2011) found that more early-summer N immobilization occurred, even to depths of 0.6 m, in compost- and manure-treated plots relative to urea-fertilized ones. This N immobilization likely decreased sugarbeet inorganic N uptake from the plots treated with compost and, somewhat less so, with manure, relative to urea (Table 8). Moreover, this N that initially had been immobilized was apparently not available for late-season uptake since sugarbeet crop quality did not decrease at Site B (Lehrsch et al., 2015). Though less noticeable, N immobilization may also have occurred at Site A where manure was applied. In 2003 at Site A, root N uptake was less where manured than urea-fertilized, in general (Fig. 1). Recall, however, that in general those manure treatments in 2003 provided less available N to the growing sugarbeet than the urea-fertilized treatment (Table 3).

In general, less N was taken up by sugarbeet tops, roots, and whole plants from the compost class than from the manure class or the Fert-B treatment (Table 8). Data for the classes have been pooled across rates since rates within amendments were similar (Table 8). The least uptake from the compost class was due to two related factors. First, the compost class supplied only about half the available N, on average, than did the manure class (Table 3). Second, where compost was applied there was likely less inorganic N available for uptake early in the 2003 growing season. Because compost is composed of relatively stable, recalcitrant carbonaceous compounds (Larney et al., 2006), its influence on microbial growth was limited (Lentz et al., 2011). On the other hand, where manure with more easily metabolized C was added, microbial populations probably increased then decreased rapidly, releasing in total much more organic N than where compost was added (Lentz et al., 2011). The N added by the Fert-B treatment was immediately available, requiring no microbial transformation of organic N to inorganic N. All sugarbeet biomass and N uptake measures responded similarly whether fertilized with urea (Fert-B) or manure (Man1-B and Man2-B as a class). The greater whole-plant biomass and root N uptake from the manure class than the compost class was a likely consequence of twice the available N being supplied by the manure than compost (Table 3) and both increased and sustained mineralization of the labile organic nitrogenous compounds prevalent in manure but not compost (Monaco et al., 2010; Lentz et al., 2011).

In general, the NR by sugarbeet at Site B resembled that at Site A (Table 6) and thus has not been shown. At Site B, the NR tended to be greatest for the Fert-B treatment, intermediate for the manure treatments, and least for the compost treatments. These trends in NR were also reported by Lentz et al. (2011), though as averages for data collected on both eroded and non-eroded soil.

The pattern of the sugarbeet NUEs at Site B (Table 9) was similar to that at Site A (Fig. 2) except that the NUEs at Site B decreased among the Fert-B and manure treatments such that Fert-B > Man1-B > Man2-B. Also similar between sites were the patterns between the fertilizer and compost treatments. The NUEs were similar between the fertilized and compost low-rate treatments, both of which were greater than the NUE of the compost high-rate treatment (Table 9 and Fig. 2). These patterns again reflect the similar available N provided by the fertilizer and low-rate compost and the greater available N provided by the high-rate compost (Table 3). The NUE values shown in Table 9 mostly fall within the NUE range [32–107 kg sucrose (kg N supply)$^{-1}$] reported by Tarkalson et al. (2012) who studied the same Portneuf silt loam. The contrasts in Table 9 reveal that sugarbeet from the Fert-B

Table 9. Agronomic nitrogen use efficiency (NUE) for sugarbeet by treatment and contrast for Site B.

Source of variation	Nitrogen use efficiency
	kg sucrose (kg available N)$^{-1}$
Treatment	
Fert-B	83.5 a†
Com1-B	76.8 a
Com2-B	35.6 b
Man1-B	41.3 b
Man2-B	16.3 c
Contrast‡	
Fert vs.	83.5 a
Com1&2	56.2 b
Fert vs.	83.5 a
Man1&2	28.8 b
Com1&2 vs.	56.2 a
Man1&2	28.8 b

† Treatment or contrast means followed by a common letter were not significantly different at $P = 0.05$.

‡ Fert = Fert-B; Com1&2 = Com1-B + Com2-B; Man1&2 = Man1-B + Man2-B.

treatment used applied N more efficiently to produce sucrose than the sugarbeet fertilized with either compost or manure. Furthermore, sugarbeet produced sucrose nearly twice as efficiently by utilizing N from compost rather than manure (Table 9), in part because only half as much available N was supplied by compost than manure, on average (Table 3).

CONCLUSIONS

1. The N uptake of sugarbeet tops at each site, but not roots, and by whole plants at Site B was similar whether fertilized with urea or an organic N source, regardless of rate. For whole plants at Site A, however, N uptake was similar between urea and only the high rate of each amendment, in general.
2. When averaged across amendment rates, N uptake of tops, roots, and whole plants was similar (i) between urea and manure for all site-years, and (ii) between urea and compost for two of three site-years, when the organic amendments were incorporated to a depth of 0.10 m. Thus, the N needs of sugarbeet can be met by the mineralization of organic N from fall-applied manure or compost, in general.
3. Incorporating organic amendments at equal rates to a depth of 0.05 rather than 0.10 m increased whole-plant N uptake.
4. Sugarbeet N uptake increased by 1.29-fold or more, on average at Site A, when the application rate (dry-weight basis) of compost increased from 53.1 to 106.1 Mg ha^{-1} in 2003 and from 64.2 to 128.4 Mg ha^{-1} in 2004. Similarly, sugarbeet N uptake increased by 1.35-fold or more when the manure rate increased from 21.9 to 43.8 Mg ha^{-1} in 2003 and from 22.8 to 45.6 Mg ha^{-1} in 2004.
5. Nitrogen recovery from each fertilizer source generally decreased in the order urea >> manure > compost. Sugarbeet recovered 41.0% of the total N in urea, 8.2% of the total N in manure, and 5.4% of the total N in compost each year, on average, from two fields at Site A. First-year recovery from organic sources was low because much of their total N remained predominantly in organic rather than inorganic forms.
6. Nitrogen use efficiency did not differ among inorganic and organic N sources for each site-year, when similar rates of available N were supplied. The NUE decreased with increasing application rates, regardless of the organic N source.
7. Producers can grow sugarbeet using organic amendments, particularly manure, in lieu of conventional inorganic fertilizer, when applied at equivalent available N rates. Both N use efficiency and N uptake will be similar to that where inorganic N would have been applied.

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